# Low-Frequency Noise of YBCO/Au Junctions

Yizi Xu, J. W. Ekin, and C. C. Clickner
National Institute of Standards and Technology
Boulder, Colorado 80303, USA

*Abstract*—**We have fabricated ex-situ c-axis YBCO/Au junctions with low contact resistivities. These devices exhibit large low-frequency resistance fluctuations. At room temperature the junction noise spectrum is 1/f like. At liquid nitrogen temperature (77 K) and lower, the noise spectrum depends sensitively on the bias current, with certain bias levels producing clear two-level fluctuation behavior. The normalized resistance noise for these junctions at temperatures below 77 K has an average value of 2 to $3\times10^{-5}$ $(Hz)^{-1/2}$. We discuss practical issues related to junction noise properties.**

## I. INTRODUCTION

Contacts of Au to high-temperature superconductor (HTS) thin films play an important role in many areas of HTS technology. In HTS electron device packaging, for example, wirebond pads are formed by depositing noble metal, usually Au, on HTS thin films, usually c-axis YBCO films. In this case, it is desirable to limit the contact resistance to less than that of the Au wire, which is about 0.1 Ω at the device operating temperatures. Since contact pad areas are typically about $5\times10^{-4}$ $cm^2$ in electronic packaging of moderate density, the contact resistivity should be less than $5\times10^{-5}$ $\Omega\cdot cm^2$ at temperatures of 77 K and below, a level which can be consistently achieved only with oxygen annealing when fabricating YBCO/Au contacts ex-situ. In other applications, such as HTS microwave circuits and HTS Josephson thermometry [1], the YBCO/Au contacts are an integral part of the circuit. Not only their resistivity, but more importantly, their noise behavior, will have significant consequences for device performance.

Several groups have studied contact resistance of c-axis YBCO/Au junctions [2-5]. However, little information is available on contact resistance noise. The purpose of the present study is to systematically measure the low-frequency noise properties of ex-situ c-axis YBCO/Au junctions.

Manuscript received September 15, 1998.

This work was supported in part by Department of Energy under Grant No. DE-IA03-94ER14420.

## II. EXPERIMENTAL

### A. Junction Fabrications

In this work we focus on ex-situ contacts, i.e., the contacts were made after the YBCO films were removed from the vacuum chamber and were subjected to contamination from air exposure, as well as photolithographic processing. Details of our ex-situ junction fabrication procedures have been reported previously [5]. For such ex-situ contacts an in-situ surface cleaning prior to Au deposition is absolutely necessary. Without such cleaning, the Au films have poor adhesion and frequently delaminate. In this work the in-situ cleaning was carried out using ion milling. We found that the resulting contact resistance depends not only on the ion beam energy but also on the milling time. The lowest contact resistivity (at liquid helium temperature) we have achieved for such ex-situ contacts, with consistency, is about $1\times10^{-4}$ $\Omega\cdot cm^2$. The corresponding ion beam energy is between 200 and 250 eV, and the milling time is between 1.5 and 2.5 mins. For energies and times outside these ranges the contact resistivity increases.

If, after the Au deposition, we immediately back fill the deposition chamber with $6.67\times10^4$ Pa (500 Torr) of oxygen, and anneal the chip at 500 C for 20 mins, the contact resistivity can be reduced to $1\times10^{-6}$ $\Omega\cdot cm^2$ range. One chip was fabricated using this sequence in order to study the effects of oxygen annealing on junction noise.

### B. Low-frequency Noise Measurement

DC bias current was applied to the devices using a deep-cycle marine battery. The voltage signal from the devices was fed to a battery-powered, low-noise preamplifier at room temperature. The input voltage noise of this preamp is white down to 6-7 Hz, and is about 1.6 $nV/(Hz)^{1/2}$. The gain of the preamplifier is fixed at 100. For quiet devices it is necessary to follow the preamplifier with another amplifier with variable gain to boost signals to proper amplitude for input to a spectrum analyzer. This second amplifier has slightly higher input voltage noise. The noise floor of the system is entirely determined by the preamplifier, however.

Shielded twisted pairs were used for all the signal wires. We were particularly careful about system grounding to minimize capacitive pick-ups. Although the devices were enclosed in a single brass can, and the measurements were carried out without using screen-room type enclosures of any sort, the noise floor of our measurement system appears to be

1051-8223/99\$10.00 © 1999 IEEE

quite adequate. For example, with a total gain of $10^4$, the total white noise of the system with a 60 Ω input resistor at room temperature was only 2.2 nV/(Hz)$^{1/2}$. Moreover, the line-frequency interference was less than 4 nV/(Hz)$^{1/2}$.

## III. Results And Discussions

### A. Conductance Characteristics

Fig. 1 shows the normalized conductance vs. voltage characteristics at 4 K for four junctions on a single chip, all with 6.4x$10^{-7}$ cm$^2$ nominal area. Each curve is normalized by the junction conductance at +150 mV. This normalization factor is chosen since junction conductance at high bias voltage is not influenced by the superconducting properties of the junction electrode(s). The curves are labeled from J1 to J4 in descending order. For clarity the curve of device J1 was offset vertically by 0.075, and that of J2 by 0.05, as indicated by the arrows associated with these curves. The curves of J3 and J4 were not offset. Additionally, the zero-bias resistance and resistivity for each junction are also listed. The resistivity

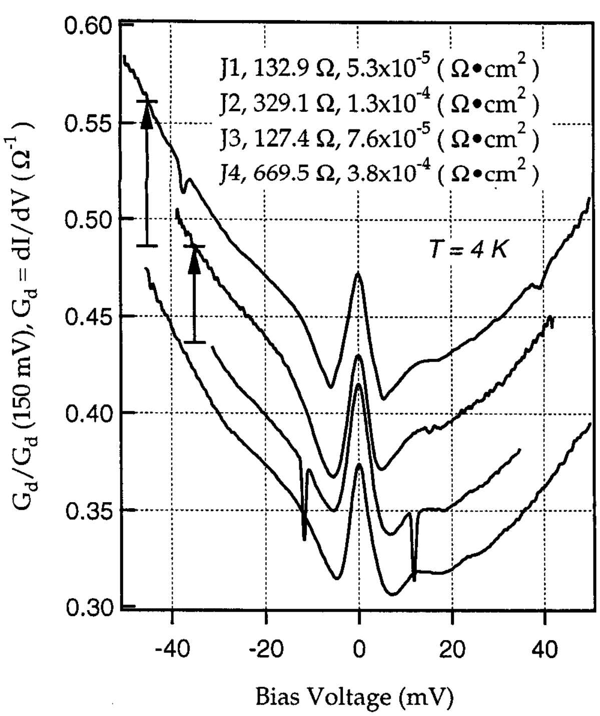


Fig. 1. Normalized conductance vs. voltage curves for four junctions on a chip at 4 K. The curves are labeled from J1 to J4 in descending order. Note that the curves for J1 and J2 are offset for clarity. The magnitude of the offset are indicated by the length of the arrow associated with each curve. Curves J3 and J4 are not offset. The junction resistances are zero-bias values, and resistivities are calculated using actual junction areas obtained from calibrated microscope images.

was calculated using the actual junction area obtained from its microscope image. The variation in the contact resistivity is considerable, and is quite common in our junctions. It is possibly due to uneveness in surface contaminants and defects distribution, and variation in ion milling rate across the chip area.

The normalized conductance characteristics are remarkably similar among the junctions. First, they all have a zero-bias conductance peak with a value which, after normalization, lies between 0.38 and 0.42. Secondly, the conductance vs. voltage characteristics are asymmetric, with forward bias being less conductive than the corresponding reverse bias (note that the forward bias condition corresponds to biasing the YBCO base electrode positively with respect to the Au counter electrode). Thirdly, there is a conductance reduction below about 16-18 mV of bias in either bias polarity. This structure is more pronounced in the forward bias branch, and is evendently related to the superconducting gap of the YBCO electrode. Lastly, there is noticeable resistance fluctuations at bias above 20 to 30 mV.

Device J3 had a conductance dip at about 12 mV in both bias branches. Similar but much less pronounced structures can be seen in J1 at about 40 mV. The latter may be attributed to a Josephson weak-link located in series with the interface resistance. When its critical current is exceeded, its normal-state resistance causes a jump in the total resistance, hence a dip in the dI/dV curve. However, the dip structure of J3 is too sharp to be explained by this model.

Note that this chip was processed with optimal conditions for ex-situ contact. Indeed, these junction resistivities are among the lowest we have measured for ex-situ contacts without annealing. Nevertheless, the contact resistance noise appears to be quite large, at least in certain bias ranges.

### B. Noise at Room Temperatures

Fig. 2 shows room temperature noise power spectrum at several bias levels for the junction J1 in Fig. 1. Since the junction had a zero-bias resistance of 60 Ω at 297 K, the "zero-bias" curve established the noise floor of the system with an input impedance of 60 Ω. At finite bias, the noise power density (NPD) displayed a clear 1/f dependence on the frequency. Moreover, when the current was increased by a factor of ten, the NPD increased one hundred times, as shown in Fig. 2 by a vertical shift of 20 dB. This quadratic dependence indicates that the fluctuation is resistive, that is, it is manifested as a voltage noise when a DC current is passed through the junction.

### C. Noise at Liquid Nitrogen Temperature

The noise power spectra for the same junction at 77 K are shown in Fig. 3 for several bias current levels. At low bias levels, the spectra deviate significantly from an 1/f dependence. In fact, they more closely resemble a Lorentzian

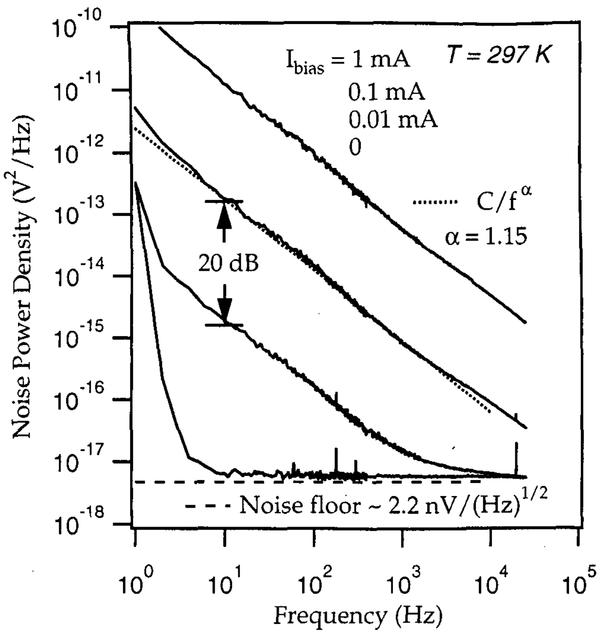


Fig. 2. Room temperature voltage noise spectra at 0, 0.01, 0.1, and 1 mA bias for device J1 in Fig. 1. The dashed line indicates the white noise floor of the amplifier system with a 60 Ω input resistor. The dotted line is a fit to the 0.1 mA spectrum. The resultant 1/f-exponent, α, is very close to one.

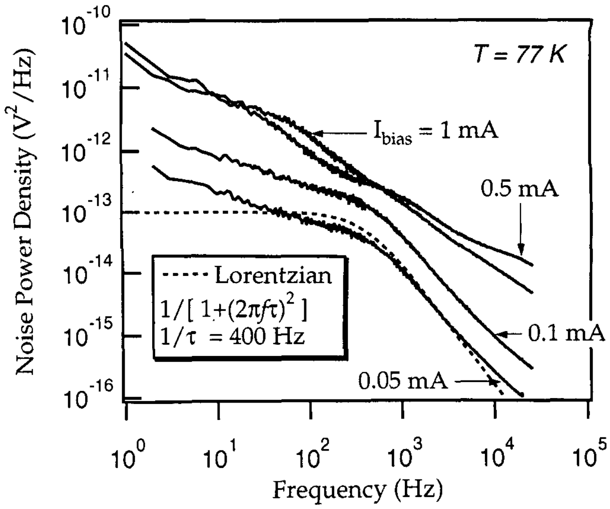


Fig. 3. Voltage noise spectra of device J1 at 77 K for 0.05, 0.1, 0.5, and 1 mA. Note that the magnitude of the 1 mA spectrum is very close to that of 0.5 mA. The spectra at 0.05 and 0.1 mA resemble the Lorentzian function, which is illustrated by the dashed line with a roll-off frequency of 400 Hz. They may indicate the existence of two-level fluctuators.

response. The dashed line in the figure is a Lorentzian function with a "knee" frequency of 400 Hz. Below this frequency, its magnitude is frequency independent. Above this frequency, it decreases with $1/f^2$. As can be seen, the Lorentzian function accurately reproduces the high frequency roll-off behavior of the spectrum.

It is well known that a random telegraph signal (RTS) will result in a Lorentzian power spectrum [6]. Physical systems containing two-level, metastable states can exhibit RTS type resistance fluctuations if a coupling between the two-level fluctuators and the electrical resistance exists. The "knee" frequency in the noise spectrum is an appropriate average of the mean life times characteristic of the two states. The noise spectra of this junction at low temperatures may suggest the existence of such two-level fluctuators which are coupled to the junction resistance.

The spectrum with 0.5 mA bias current is very interesting. There appear to be two "bumps", and perhaps a third one at high frequencies. Rogers and Buhrman have demonstrated, in small Nb tunnel junctions, that such structures may be produced by several two-level fluctuators, each with its own characteristic knee frequency, acting independently [7].

At still higher bias, 1 mA, the spectrum changed again. Its overall magnitude was actually very similar to that of the 0.5 mA bias. Clearly, the noise behavior at 77 K is more complicated. The simple quadratic dependence on the bias current at room temperatures no longer holds.

### D. Noise at Liquid Helium Temperature

The influence of the two-level fluctuators on the junction resistance noise is best illustrated in Fig. 4, which displays the conductance of the same device J1 at 4K as a function of bias current. Note that the data are considerably noisier in the 0.3 mA to 0.5 mA bias range (the area indicated by the box with light gray frame). The typical fluctuation magnitude was (1-2) Ω. To understand this, we need to look at the junction noise behavior at 4 K. The inset of Fig. 4 shows the noise spectra for 0.4 mA and 0.25 mA bias. Note that the 0.4 mA spectrum is essentially flat from 10 Hz to about 1000 Hz, and at 500 Hz (the dashed line) the NPD was about $10^{-12}$ $V^2$/Hz. Since the AC modulation used for our lock-in detection was also at 500 Hz, and since the time constant of the lock-in amplifier was set to 30 ms, equivalent to a bandwidth of 5 Hz, we should expect a total root-mean-squared (rms) voltage fluctuation in our detection bandwidth of about $2\times10^{-6}$ volts. The rms amplitude of the modulation current was $1.5\times10^{-6}$ amps. So the voltage noise should result in a resistance noise of 1-2 Ω. This agrees well with the actual conductance data. At lower bias current levels, for example at 0.25 mA, the junction NPD at 500 Hz was about ten times lower, hence a proportionately smaller resistance noise.

### E. Normalized Resistance Noise

From a practical point of view, a more interesting figure is the normalized resistance noise. This quantity is generally frequency dependent. Fig. 5 plots this quantity at 10 Hz for device J1 at three temperatures: room temperature, 77 K and 4 K. Data for two bias levels are presented.

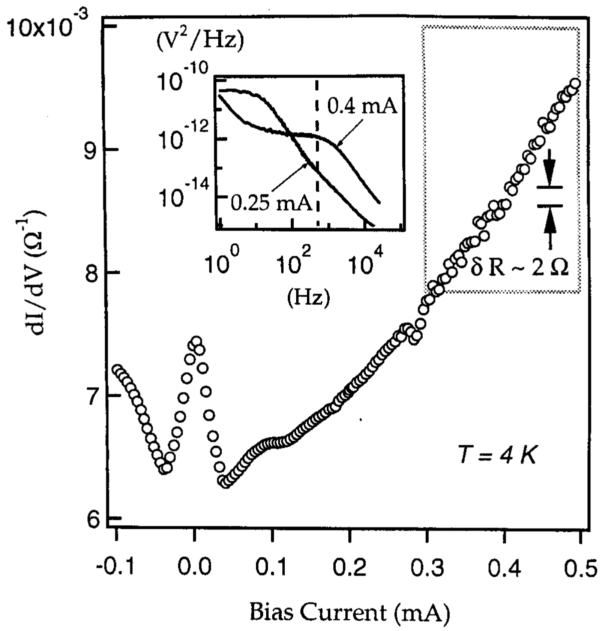


Fig. 4. Conductance vs. bias current for device J1 at 4 K. The noisy data at high bias range (indicated by the gray frame box) may be understood by the bias dependence of the junction voltage noise spectrum, which is shown in the inset for two current levels.

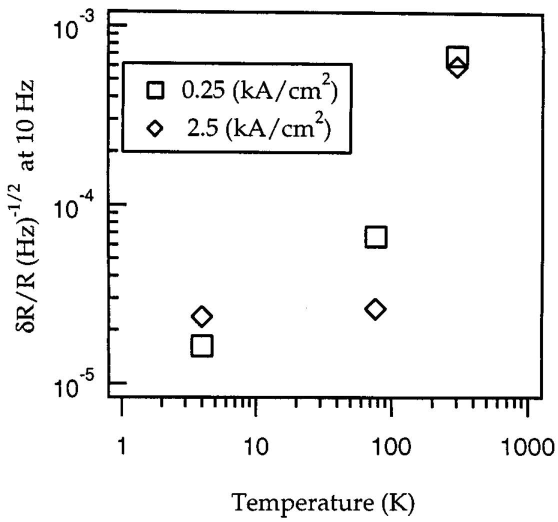


Fig. 5. Normalized resistance noise at 10 Hz for J1 as a function of temperature for two bias levels. Below 77 K the temperature dependence appeared to be weak, especially for the high bias level. The average value in this temperature range is $(2\text{-}3)\times10^{-5}$ (Hz)$^{-1/2}$.

At room temperatures the data are not sensitive to the bias level. At temperatures below 77 K, the data showed stronger bias dependence. However, the temperature dependence of the normalized resistance noise appears to be mild at low temperatures. The average value is about $(2\text{-}3)\times10^{-5}$ (Hz)$^{-1/2}$. In our oxygen annealing experiment we were able to make junctions whose interface resistivity at 4 K reached a much lower value of $1\times10^{-6}$ $\Omega\cdot cm^2$, almost a factor of one hundred smaller than the unannealed junctions reported here. Their voltage noises were proportionately smaller. However, their normalized resistance noise was about $1\times10^{-5}$ (Hz)$^{-1/2}$, comparable to the unannealed devices.

## IV. Conclusions

These junctions, which represent the lowest interface resistivities ($1\times10^{-4}$ $\Omega\cdot cm^2$) that can be obtained in ex-situ c-axis YBCO/Au junctions without annealing, all show surprisingly high level of resistance noise. At room temperature the resistance noise is 1/f like and not sensitive to the bias level. At 77 K and below, however, the noise spectra are strongly influenced by the bias level, with certain bias ranges producing Lorentzian noise spectra that remained flat up to about 1000 Hz. Consequently, when such junctions are used in detection systems, design issues such as bias point, operating frequency, and detection bandwidth have to be critically evaluated with respect to junction noise behavior.

Oxygen annealing has been known to be a practical and effective method to reduce the contact resistivities in the c-axis YBCO/Au junctions. We have evidence that it also reduces the junction voltage noise effectively. However, when the normalized resistance noise is concerned, the mitigating effect of oxygen annealing appears to be quite limited.

## References


[1] J. C. Gallop and B. W. Petley, "Josephson Noise Thermometry with HTS Devices," *IEEE Trans. Instrum. and Measure.*, Vol. 44, pp. 234-237, April, 1995.

[2] J. W. Ekin, S. E. Russek, C. C. Clickner, and B. Jeanneret, "In situ noble metal $YBa_2Cu_3O_7$ thin-film contacts," *Appl. Phys. Lett.*, Vol. 62, p. 369, 1993.

[3] Z. H. Gong, J. K. Grepstad, and R. Fagerberg, "The YBCO(001)/Ag interface: correlation between specific contact resistance and interfacial microstructure," *IEEE Trans. Appl. Supercond.*, Vol. 5, pp. 2412-2415, June, 1995.

[4] H. Terai, A. Fujimaki, Y. Takai, and H. Hayakawa, "Electrical interface structure in $YBa_2Cu_3O_{7-x}$/metal contacts," *IEEE Trans. Appl. Supercond.*, Vol. 5, pp. 2408-2411, June, 1995.

[5] Yizi Xu, J. W. Ekin, C. C. Clickner, and R. L. Fiske, "Oxygen Annealing of YBCO/Gold Thin-Film Contacts", *Advances in Cryogenic Engineering - Materials*, Vol. 44. Plenum: New York, 1998.

[6] Stefan Machlup, "Noise in Semiconductor: Spectrum of a Two-Parameter Random Signal," *J. Appl. Phys.*, Vol. 25, pp. 341-343, March, 1954.

[7] C. T. Rogers and R. A. Buhrman, "Composition of 1/f Noise in Metal-Insulator-Metal Tunnel Junctions," *Phys. Rev. Lett.*, Vol. 53, pp. 1272-1275, Sept. 1984.